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TOPO-OZ: Insights into the various modes of intraplate deformation in the Australian continent

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ABSTRACT

As the fastest, lowest, flattest and amongst the most arid of continents, Australia preserves a unique geomorphic record of intraplate tectonic activity, evidencing at least three distinct modes of surface deformation since its rapid northward drift commenced around 43 million years ago. At long wavelengths (several 1000s km) systematic variations in the extent of Neogene marine inundation imply the continent has tilted north–down, southwest–up. At intermediate-wavelengths (several 100s km) several undulations of ~100–200 m amplitude have developed on the 1–10 myr timescale. At still shorter wavelengths (several 10s km), fault related motion has produced local relief at rates of up to ~100 m/myr over several million years. The long-wavelength, north–down tilting can be related to a dynamic topographic effect associated with Australia's northward drift from the geoid low, dynamic topography low now south of the continent to the geoid high, dynamic topography low centred above the south-east Asian and Melanesian subduction zones. The short wavelength, fault-related deformation is attributed in time to plate-wide increases in compressional stress levels as the result of distant plate boundary interactions and, in space, in part to variations in the thermal structure of the Australian lithosphere. At the intermediate wavelengths, transient, low amplitude undulations can be ascribed to either lithospheric buckling or the development of instabilities in the thermal boundary layer beneath the lithosphere. In the latter case, topographic asymmetries suggest the Australian lithosphere is moving north with respect to the mantle beneath, providing a unique attribution to the progressive alignment of seismic anisotropy and absolute plate motion observed near the base of the Australian lithosphere.

1. Introduction

Australia is the lowest and flattest of all continents, consistent with relatively low-levels of tectonic activity to be expected for a continent that has remained remote from active plate boundaries throughout the Cainozoic (Veevers, 1984). However, low-level tectonic activity is indicated by widespread earthquake activity (Leonard, 2008), and seismic moment release rates are elevated relative to many other stable continental regions (Braun et al., 2009; Johnston et al., 1994). A rich palaeo-seismic record of surface fault breaks and Quaternary faults (Crone et al., 2003; Crone et al., 1997; Quigley et al., 2006) raises intriguing questions about the longer-term record of tectonic activity in the continent. As part of the Indo-Australian plate (IAP), Australia is also the fastest moving continent having drifted northwards ~3000 km over the last 45 myr (Fig. 1). In so doing it has passed over a complex deep mantle density structure as revealed partly by a ~60 m differential in the geoid field across the continent, as well as the unusual ocean bathymetry of the Southern Ocean in the vicinity of the Australian–Antarctic discordance — or AAD (Gurnis et al., 1998). The dynamic topographic effects of such differential motion between the plate and the underlying mantle are significant, and most clearly evident in a fundamental asymmetry in the morphology and stratigraphic relations of its margins (Sandiford, 2007).

A further attribute of geomorphic significance is that Australia is amongst the most arid of continents. Aridity has affected much of the interior part of the continent through the late Cainozoic (Bowler, 1976), providing it with a remarkable geomorphic 'memory'. The exquisite detail preserved in extremely old landforms, such as the Eocene beach barrier systems and associated lagoons on the eastern Nullarbor Plain (Fig. 2), imply surface processes have been remarkably ineffective. This preservation of ancient palaeo-shorelines and lake systems, in particular, allows for unambiguous reconstruction of subtle deformations of the landscape, the memory of which would have been greatly obscured or obliterated in environments characterised by more active surface processes.

The last few years have seen a resurgence of interest in the tectonic geomorphologic record of the Australian continent (Celerier et al., 2005; Quigley et al., 2007a,b; Sandiford, 2003a,b, 2007, 2004). Parallel studies have established a basic framework for understanding key neotectonic

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'drivers' such as the *in situ* stress state (Coblentz et al., 1998; Hillis and Reynolds, 2000; Reynolds et al., 2002; Sandiford et al., 1995, 2004) mantle structure (Debayle et al., 2005; Kennett et al., 2004) and thermal regime (McLaren et al., 2003; Neumann et al., 2000). In this paper we review the main insights gained from these studies. We begin with a brief summary of the current geodynamic state of the Australian continent, including our current knowledge of the *in situ* stress and geoid fields and constraints on deformation rates provided by the seismic record. We then explore the neotectonic record at a variety of scales. This record in interpreted in terms of three distinct modes of deformation each with a characteristic temporal and spatial scale. At the shortest wavelength (order 10^1–10^2 km) active faulting is demonstrably shaping the landscape in several parts of the continent and can be related to propagation of stress from distant plate boundaries. At intermediate wavelengths (order 10^2–10^3 km) low amplitude undulations have produced distinctive patterning of continental relief most clearly associated with modern and palaeo-lake systems. Finally, at the longest wavelength (>10^3 km) a pattern of continental tilting can be related to dynamic topography associated with its northward passage from the geoid low, dynamic topography high now lying south of the continent, to a geoid high, dynamic topographic low centred over the subduction zones of South East Asia and Melanesia.

Our prime concern is on the topographic record of the Australian continent in the context of the evolution of the IAP. The IAP was born of a complex sequence of correlated events that saw the fusion of the Indian and Australian plates around 45 million years ago (Fig. 1). The critical element of this was the termination of spreading in the north-central Indian Ocean that accompanied deceleration of the Indian plate during the initial stages of Himlayan collision (Patriat and Achache, 1984), and the associated northward acceleration of the Australian Plate (Gaina and Muller, 2007). Prior to 50 million years ago Australia formed the core of a much more slowly moving plate largely surrounded mid-ocean ridges. As such, its palaeo-geographic setting was more reminiscent of the present-day Africa, in the sense of having a higher degree of symmetry in the plate boundaries compared to today (Fig. 1b). With termination of spreading in the north central Indian Ocean and the Tasman Sea to the east of Australia, Australia became one of two continental crustal fragments (the other being India) fused into a fast moving plate with strongly asymmetric boundary configurations (mid-ocean ridges to the south, convergent margins to the north). The onset of the modern compressional intraplate stress field (see below) most probably dates to this transition, with the pre-Eocene continent likely to have been subject to mild extensional stress regimes, in analogous fashion to the African continent (Coblentz and Sandiford, 1994; Sandiford and Coblentz, 1994; Sandiford et al., 1995).

Understanding just how the Australian landscape has been modified by, and records, subtle tectonic processes should inform how to isolate comparable signals in other slower moving, faster eroding settings such as Europe (Cloetingh et al., 2005). With international programs such as TOPO-EUROPE now focussing interdisciplinary work on all manner of phenomenon related to the topographic evolution of the continents, our purpose here is simply to briefly summarise our recent insights from Australia that link the active deformation to the contemporary geodynamic setting and

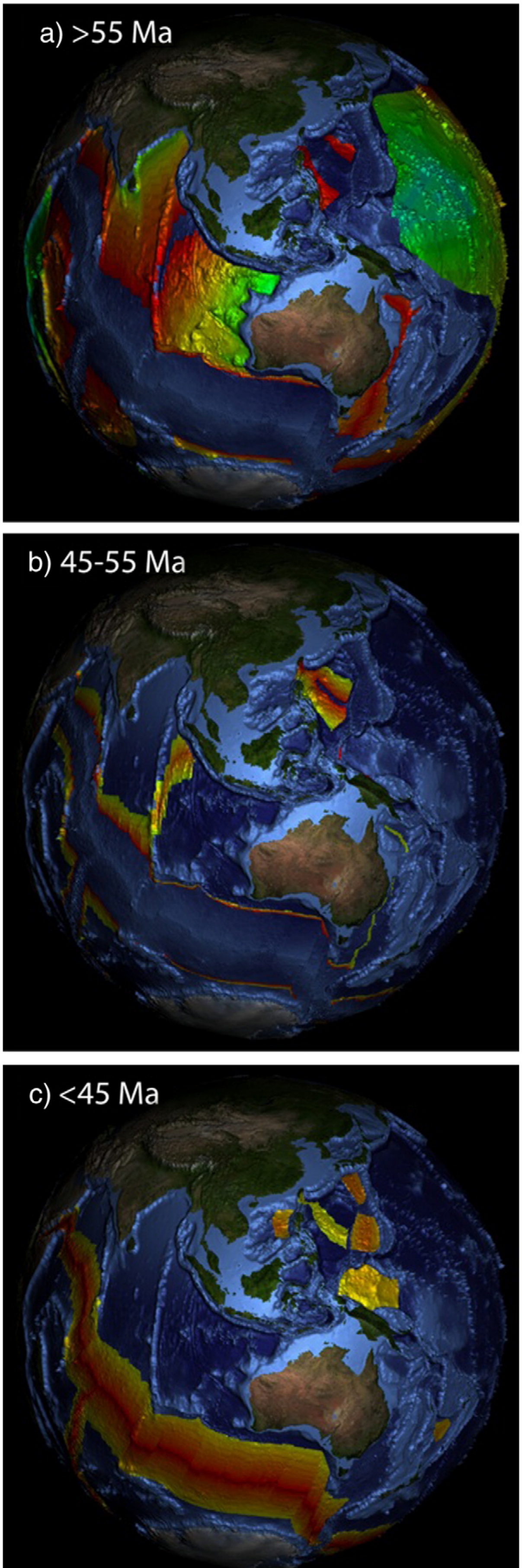

Fig. 1. (a) Ocean-floor evolution in the Indo-Australian plate as reflected in the surrounding ocean floor ages. Prior to 45 million years India and Australia formed parts of distinct plates separated by spreading in the central Indian Ocean (a, b). At this time Australia was largely surrounded by active ridge systems, much like modern Africa. Australia's rapid northward drift commenced after amalgamation of the Indian and Australian plates at ~43 Ma (c). Colors reflect relative sea floor age from green (old) – yellow – red (young). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)